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USE OF ANALYTICAL METHOD FOR DETERMINATION OF MATERIAL PROPERTIES OF PULTRUDED GRP BOX SECTION

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Abstrac — **Glass reinforced plastic (GRP) structural members are currently being produced successfully by pultrusion and are used in an increasing number of civil engineering applications. Measurement of the mechanical properties of the composite material is necessary for numerical structural analysis and design. The mechanical properties of composite materials are determined by specific coupon test methods or by analytical models (giving estimated linear elastic properties). However, the experimental test method may not economical or practical for the determination of mechanical properties of pultruded GRP structural sections. The elastic properties of the pultruded GRP box section have been estimated using micro-mechanical models and classical lamination theory. ASTM D3039 specimens have been used to provide the experimental longitudinal tensile properties of pultruded GRP box section to verify the analytical method.**

Index Terms — **Glass reinforced plastic, mechanical properties, micro-mechanical model, classical lamination theory.**

I. INTRODUCTION

Within the past four decades there has been a rapid increase in the development of advanced composites incorporating fine fibres, termed fibre reinforced composites. These materials, depending on the matrix used, may be classified as a polymer, metal, or ceramic matrix composites. The high cost of metal and ceramic matrix composite materials prevents their normal use in construction. The majority of composites used in the construction industry are therefore based on polymeric matrix materials. Additional factors in choosing polymeric composite materials for structural engineering applications are: the materials are lightweight, non-corrosive, chemically resistant, possess good fatigue strength, are non-magnetic, and, subject to the materials selected, can provide electrical and flame resistance. Material surfaces are also durable and require little maintenance [1].

Most of the pultruded glass reinforced plastic (GRP) sections are available in the form of thin walled sections (i.e. Fibreforec 800 series, EXTREN). Generally, thin walled pultruded GRP sections are composed of laminae containing different fibre orientations and forms [2, 3]. It is possible to estimate the elastic properties of composite sections using micro-mechanical models (to obtain the properties of individual layers) and Classical Lamination Theory (CLT) (for the complete section) in terms of the geometry, distribution and volume fraction of the fibres, and the elastic properties of the fibres and matrix (Hull, 1981). For example, Davalos *et al* [3] and Sonti and Barbero [4] obtained the ply properties through micro-mechanics and then used CLT [5] to predict the section properties of pultruded GRP profiles (I-section, wide flange).

In this study, the extensional modulus, E_x, its transverse component, E_y, and Poisson's ratio, ν_{xy}, were estimated. The fibre volume fraction of each ply is defined as the ratio of the volume of fibres present in a layer to the total volume of that layer. In the case of the box section used in this study, information related to the fibre volume fraction of each layer has been provided by Mottram [6] and are presented in Table 1. The mechanical properties of the fibre and the matrix, given in Table 2, are used to calculate elastic properties of each layer using micro-mechanics. The outcomes of these calculations are then used in a macro-mechanical model to estimate the material properties of the composite through classical lamination theory (CLT). Experimentally determined tensile properties were compared with analytical predictions.

II. ESTIMATED ELASTIC PROPERTIES

II-I. Construction of Box Section

The pultruded GRP box section (see Plate 1) (obtained from Lionweld Kennedy (LWK), Middlesborough, UK

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and supplied originally by Fibreforce Composites, UK) is commercially available and currently used in secondary structural applications (i.e. small frames, stairways, etc.). It has average external dimensions of 51mm and wall thickness of 3.1mm. The box section composition includes the following four types of layers (Fig. 1):

1. A veil, which is a resin-rich layer primarily used as a protective coating against erosion and surface damage to the main fibre reinforcement and to provide a smooth surface for handling. (0.065mm)
2. Continuous Filament Mats (CFM) of different weights consist of randomly orientated fibres. CFM serves to improve the transverse mechanical properties of the pultruded section. (1.547mm)
3. Plain Roving (PR) comprising continuous unidirectional fibre bundles, which contribute most significantly to the stiffness and strength of the section in the longitudinal direction. (1.420mm)
4. Mock Spun Roving (MSR) which is crimped to guide the inner CFM. (0.068mm)

This construction of the box leads to a strongly orthrotopic material, which, when thin, may be assumed to behave under plane-stress conditions. Owing to the high percentage of fibres in the longitudinal direction, both corresponding axial and bending stiffnesses are high. Conversely transverse and shear stiffnesses are both relatively low leading to anisotropic characteristics.

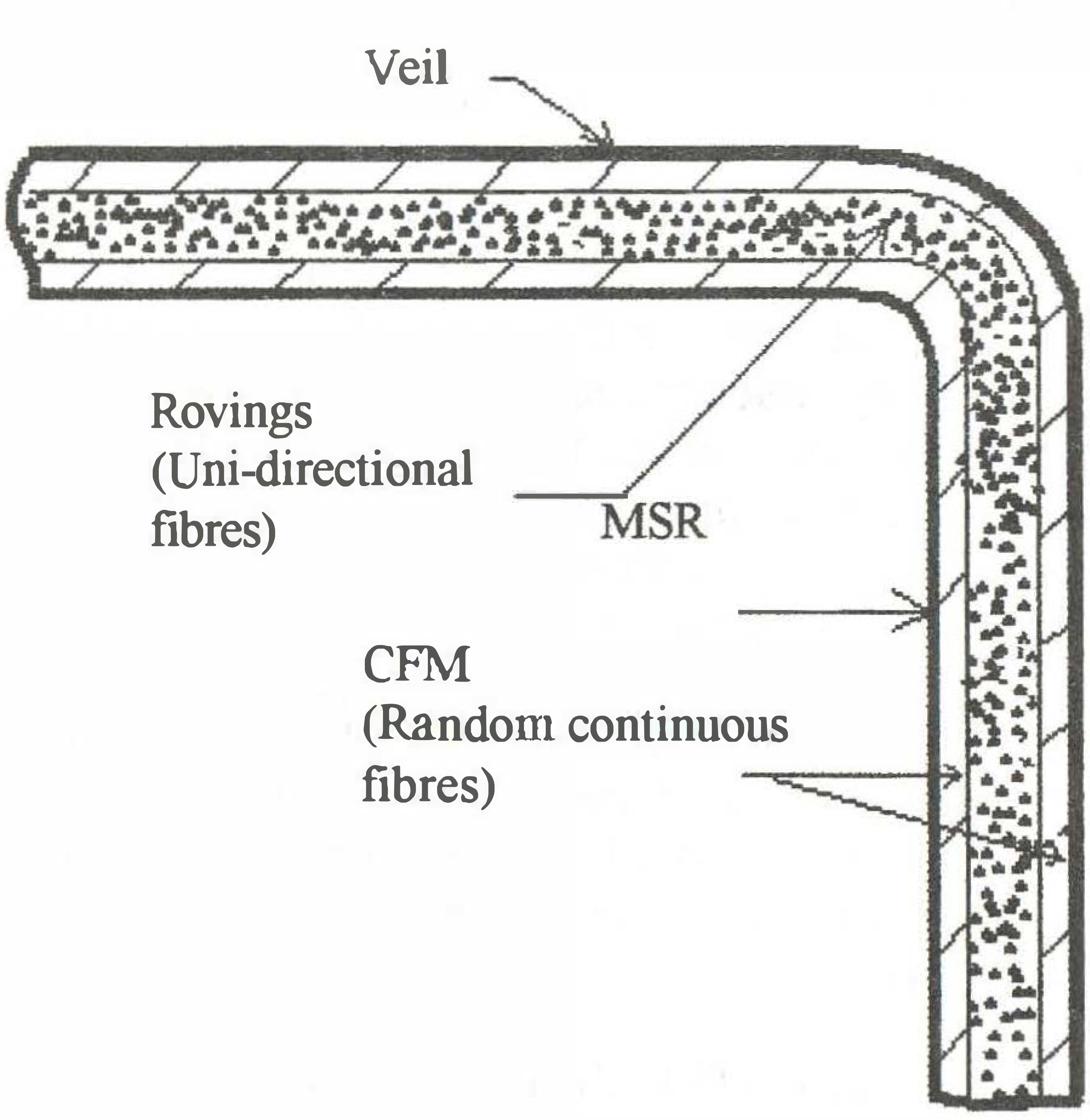

Fig. 1. Typical construction of a pultruded GRP box section.

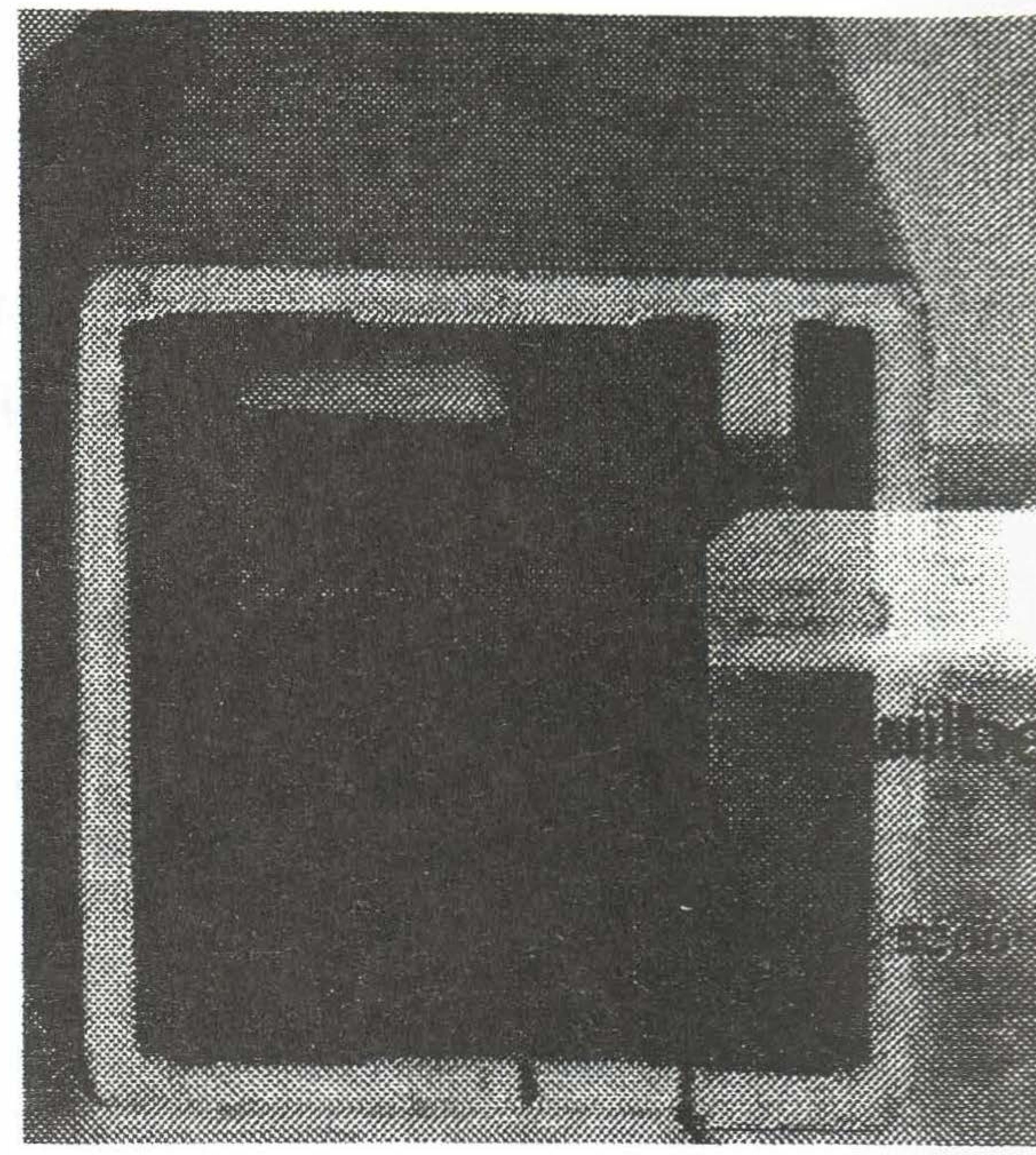

Plate 1. Pultruded GRP box section.

II-II. Micromechanics

Consistent with its construction (Fig. 1), the box sectio is subdivided through the wall thicknesses into layer where fibres are approximately unidirectional (i.e. plai rovings) and where they are much more randoml distributed (i.e. veil, CFM, MSR).

As a lamina with unidirectional fibres, the materi properties (E_x, E_y, G_{xy} and ν_{xy}) of the layer (lamin containing the plain rovings can be estimated from th "rule of mixtures" [5]. If the fibre volume fraction alo an axis, x, aligned with the main fibre direction is then the elastic modulus in that direction, E_x, is given b

$$E_x = E_f V_f + E_m(1 - V_f) \qquad \text{(Eq. 1a}$$

where E_f and E_m are the modulus of elasticity of th fibres and matrix (resin), respectively.

The orthogonal elastic modulus of the lamina, E_y, th shear modulus, G_{xy}, and Poisson's ratio in xy plane, ν are obtained as, respectively,

$$E_y = \frac{E_f E_m}{V_f E_m + (1 - V_f) E_f} \qquad \text{(Eq. 1b}$$

$$G_{xy} = \frac{G_f G_m}{(V_f G_m + (1 - V_f) G_f)} \qquad \text{(Eq. 1c}$$

$$\nu_{xy} = \nu_f V_f + \nu_m (1 - V_f) \qquad \text{(Eq. 1d}$$

with $G_{f,m}$ and $\nu_{f,m}$ the respective shear moduli a Poisson's ratios of the fibres and matrix.

Substituting the volume of V_f, E_f, E_m, G_f and G_m from Tables 1 and 2 into (Eq.1a-d), the calculated material properties for the plain rovings (PR) lamina are obtained as summarised in Table 3.

The veil, CFM and MSR laminae are made up of long-fibre filament mats in which the fibres are randomly distributed and impregnated with resin. The elastic properties of this type of a lamina may be considered to be macroscopically isotropic in the plane of the lamina provided that the fibres are randomly distributed (where "randomly distributed" is taken to mean that there exists a uniform probability distribution in the plane). The "long fibre" requirement means that the effect of fibre ends can be ignored in estimating the elastic properties [5].

Akasaka [7] derived expression giving the isotropic elastic constants (elastic modules, $\overline{E}$, shear modules $\overline{G}$, and Poisson's ratio, $\overline{\nu}$, (Eq. 2(a-c)) for macroscopically isotropic (in the plane) laminae in terms of the orthrotopic values obtained from (3.1a-b).

$$\overline{E} = \frac{3}{8}E_x + \frac{5}{8}E_y \qquad \text{(Eq. 2a)}$$

$$\overline{G} = \frac{1}{8}E_x + \frac{1}{4}E_y \qquad \text{(Eq. 2b)}$$

$$\overline{\nu} = \frac{\overline{E}}{2\overline{G}} - 1 \qquad \text{(Eq. 2c)}$$

Substituting the appropriate values from Tables 1 and 2 into (Eq. 1a-b) and using these results in (Eq. 2(a-c)), the isotropic elastic properties of the veil, CFM and MSR layers are obtained (Table 3).

II-III. Macromechanics (CLT)

By combining the elastic properties of the idealised individual laminae with the lay-up information, the mechanical characteristics of the composite can be estimated from a macromechanics approach. A commonly used method is CLT in which the following assumptions apply:

- the composite comprises perfectly bonded layers (laminae) which do not slip relative to each other,
- each layer is a homogeneous thin sheet with known effective material properties,
- individually layer properties can be isotropic, orthotropic, or transversely isotropic, with each layer in a state of plane stress.

The stress-strain relation for a single orthotropic "lamina" in a state of plane stress where the principle material axes are aligned with x-y system can be derived from the generalised form as [5],

$$\begin{Bmatrix} \sigma_x \\ \sigma_y \\ \tau_{xy} \end{Bmatrix} = \begin{bmatrix} Q_{11} & Q_{12} & 0 \\ Q_{12} & Q_{22} & 0 \\ 0 & 0 & Q_{66} \end{bmatrix} \begin{Bmatrix} \varepsilon_x \\ \varepsilon_y \\ \gamma_{xy} \end{Bmatrix} \text{ or } \overline{\sigma} = \overline{QE} \qquad \text{(Eq. 3)}$$

where the stiffness components Q_{11}, Q_{12}, Q_{22}, Q_{66} are given in terms of the constitutive material properties, as in,

$$Q_{11} = \frac{E_x}{1-\nu_{xy}\nu_{yx}}, \qquad Q_{22} = \frac{E_y}{1-\nu_{xy}\nu_{yx}}$$

$$Q_{12} = \nu_{xy}Q_{22} = \nu_{yx}Q_{11}, \qquad Q_{66} = G_{66}$$

The strain-stress relations in terms of compliance $\overline{S} = \overline{Q}^{-1}$ are given by,

$$\begin{Bmatrix} \varepsilon_x \\ \varepsilon_y \\ \gamma_{xy} \end{Bmatrix} = \begin{bmatrix} S_{11} & S_{12} & 0 \\ S_{12} & S_{22} & 0 \\ 0 & 0 & S_{66} \end{bmatrix} \begin{Bmatrix} \sigma_x \\ \sigma_y \\ \tau_{xy} \end{Bmatrix} \text{ or } \overline{\varepsilon} = \overline{S\sigma} \qquad \text{(Eq. 4)}$$

$$\left.\begin{aligned} S_{11} &= \frac{1}{E_x} \rightarrow E_x = \frac{1}{S_{11}}, \\ S_{22} &= \frac{1}{E_y} \rightarrow E_y = \frac{1}{S_{22}}, \\ -S_{12} &= \frac{\nu_{xy}}{E_x} = \frac{\nu_{yx}}{E_y} \rightarrow \nu_{xy} = -S_{12}E_x, \\ S_{66} &= \frac{1}{G_{xy}} \rightarrow G_{xy} = \frac{1}{S_{66}} \end{aligned}\right\} \qquad \text{(Eq. 5)}$$

Extending this special case of a single layer "lamina" case to N layers (laminae) then the components of $\overline{Q}$ are replaced as,

$$\overline{Q}_{ij} \rightarrow A_{ij} = \sum_{k=1}^{N} (\overline{Q}_{ij})_k t_k \quad (i,j = 1,2,6) \qquad \text{(Eq. 6)}$$

to make $\overline{A}$, with t_k the thickness of lamina k.

Similarly, $\overline{S}$ is replaced by $\overline{\alpha}$ with the $\overline{\alpha} = \overline{A}^{-1}$ defined as the compliance matrix of the laminate.

Extending the multi-layer principle to (Eq. 5), the material properties of the laminate of thickness t ($t = \sum_{k=1}^{N} t_k$) are obtained as [3],

$$E_x = \frac{1}{\alpha_{11} \times t}; \quad E_y = \frac{1}{\alpha_{22} \times t};$$

$$G_{xy} = \frac{1}{\alpha_{66} \times t}; \quad -\nu_{xy} = \alpha_{12} \times E_x \times t \qquad \text{(Eq. 7)}$$

for the box section under consideration, using the layer material properties given in Table 3, then

$$\overline{A} = \begin{bmatrix} 90.59 & 14.01 & 0 \\ 14.01 & 36.60 & 0 \\ 0 & 0 & 12.43 \end{bmatrix} \quad \text{and}$$

$$\overline{\alpha} = \begin{bmatrix} 0.01177 & -0.00451 & 0 \\ -0.00451 & 0.02914 & 0 \\ 0 & 0 & 0.08071 \end{bmatrix}$$

Substituting the values of $\overline{\alpha}$ into (Eq. 7) with t=3.1mm, estimates of the box section orthrotopic material properties are obtained (Table 4).

Table 1. Box section layer (lamina) composition [6].

	PR	**Veil**	**CFM**	**MSR**
Fibre volume fraction (V_f) %	62	24	28	56
Layer (lamina) thickness (mm)	1.420	0.065	1.547	0.068

Table 2. Constituents material properties [6].

Material	**Tensile Mod.** (kN/mm^2)	**Shear Mod.** (kN/mm^2)	**Poisson's Ratio**	**Density** (g/cm^3)
E-Glass	72 (E_f)	29 (G_f)	0.25 (ν_f)	2.56
Matrix	3.5 (E_m)	1.6 (G_m)	0.35 (ν_m)	1.24

Table 3. Layer (lamina) calculated material properties.

	E_x (kN/mm^2)	**E_y** (kN/mm^2)	**ν_{xy}**	**G_{xy}** (kN/mm^2)
PR	45.97	8.53	0.29	3.86
Veil	10.31	10.31	0.42	3.63
CFM	11.48	11.48	0.43	4.03
MSR	20.37	20.37	0.43	7.11

Table 4. Estimated elastic properties of the box section.

	E_x (kN/mm^2)	**E_y** (kN/mm^2)	**G_{xy}** (kN/mm^2)	**ν_{xy}**
Box section	27.36	11.00	4.00	0.38

III. CONCLUSIONS

The elastic properties of the pultruded GRP box section have been established using micro-mechanical models and classical lamination theory. The analytical calculations have been validated using experimental results of coupons specified from the ASTM D3039 [8]. The average longitudinal elastic modulus from five coupons was 26.7 kN/mm^2 and the Poisson's ratio was 0.29 [9]. This experimental value of elastic modulus is close to the analytical calculation (27.4 kN/mm^2) obtained from CLT. However, the experimental value of major Poisson's ratio is lower (0.29) than the analytical calculation (0.38). It implies that CLT can estimate the longitudinal properties more accurately than the Poisson's ratio.

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